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Simulation and Experimental Investigation of a PV Pumping System in Delta Region, Egypt

نمذجة وتحقيق عملي لنظام ضخ فوتوفولتي بدلتا مصر

Hassan Ahmed AbdulGhani and Eid Abdelbaki Gouda

KEYWORDS:
Photovoltaic Pumping System (PVPS), Maximum Power Point Tracking (MPPT), System Modeling, Dynamic Performance Analysis, Temperature Effect and Experimental Setup System.

***الملخص العربي*:- تناول البحث موضوعاً من الموضوعات الهامة والحديثة في مجال إستخدام الطاقة الشمسية، وخاصة في تطبيقات ضخ المياة فقد تم إستنتاج معادلات جديدة لحساب الإشعاع الشمسي اليومي في جمهورية مصر العربية. وتم عمل نموذج رياضي متكامل لمنظومة الخلايا الشمسية والموصلة مباشرة لتغذية وإدارة الطلمبات، كما تم حساب الأداء للمنظومة بإستخدام قيم الإشعاع الشمسي المستنتجة من المعادلات الرياضية. وتم تطبيق النموذج الرياضي لحساب الأداء مع أحد الأنواع من المحركات الكهربية التي تقوم بتشغيل الطلمبة. وقد أمكن دراسة تأثير درجة حرارة الخلايا وطرق الحصول على القدرة القصوى على الأداء الكلي والكفاءة الكلية للمنظومة، كما تم عمل نموذج ديناميكي لمعرفة تأثير التغيير المتوقع في قيم الإشعاع الشمسي على الأداء والخواص الكهربية للمحركات الحثية. كما تمت مقارنة النتائج المحسوبة بالقيم المقاسة عملياً وإتضح من النتائج دقة النماذج الرياضية المستخدمة. وأمكن كذلك القيام بقياسات عملية مع دراسة الأداء الكهربي للنموذج العملي، وذلك بالقياس المستمر لهذه المتغيرات على مدى زمني متصل وملاحظة تغيير التردد والتشوه نتيجة تغيير الإشعاع الشمسي.**

***Abstract*—A detailed developed model for the average radiation calculated by using instantaneous values is introduced. The proposed model can be used to calculate the photovoltaic pumping system performance such as water flow rate, water head, total output power and system efficiency at a given time. An experimental system is established in Egypt Delta region located at latitude of 30.5° north and longitude of 30.3° east. The effect of cell temperature variation is studied. All meteorological data and actual measurements are collected instantaneously and stored. A comparison study between experimental and simulation results is given. Also the average water discharge predicted has been compared with the experimental values. It is found that the difference between the simulation results and the experimental is less than 5% this ensures that the proposed system is designed in high accuracy.**

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Hassan Ahmed AbdulGhani is with the Electrical Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, P.O. Box 35516, Egypt. (e-mail:hassan.eg@gmail.com)

Eid Abdelbaki Gouda is with the Electrical Engineering Department, Mansoura University, Faculty of Engineering, Mansoura, P.O. Box 35516, Egypt. (e-mail:eid.gouda@yahoo.fr)

Nomenclature:

S_{max}	:Monthly mean value of maximum possible sunshine hours per day length (hr/day)
S	:Monthly mean sunshine hours per day (hr/day)
ω_s	:Mean sunrise hour angles (degree°)
G_{sc}	:Solar constant = 1367 (W/m^2)
H_g	:Monthly average of daily global radiation per day on a horizontal surface at a specific location in (kJ/m^2-day)
H_o	:Monthly average of daily extra-terrestrial radiation which would fall on a horizontal surface in the absence of atmosphere at particular location (kJ/m^2-day)
a, b	:Regression coefficients
ϕ	:Latitude angle of the site (degree°)
δ	:Solar declination angle (degree°)
I_d	:Solar radiation direction through scattering by the atmosphere (W/m^2)
I_g	:Sum of beam and diffuse radiation (W/m^2)
I_L	:Cell current which is equal to short circuit current (A)
I_o	:Reverse saturation (dark) current (A)
I_{sc}	:Short-circuit current (A)
q	:Electron charge = 1.602×10^{-19} (Coulomb)(EV)
k	:Boltzmann constant = 1.381×10^{-23} (J/K)
T	:PV cell temperature (°K)
I	:Photovoltaic cell current (A)
V	:Photovoltaic cell voltage (V)
F	:Photovoltaic Cell fill factor

P	:Power output of the photovoltaic cell (W)
T_e	:Electromagnetic torque (N.m)
T_L	:Load torque (N.m)
J	:Moment of inertia (Kg.m^2)
B_m	:Friction factor (N.m.s)
ω_m	:Motor angular speed (rad/s)
P_u	:Useful power (W)
D	:Load speed dependent constant = 6.57×10^{-4} (N.m.s^2)
Q	:Water flow rate (m^3/s)
H	:Total head (m)
ρ	:Water density = 1000 (kg/m^3)
g	:Earth gravity = 9.81 (m/s^2)

I.INTRODUCTION

THE main components of any photovoltaic pumping system are the PV array, the electrical motor, the water pump and a suitable inverter. Normally the electrical motor is directly coupled to the pump unit. A sufficient radiation level must be available to enable the system starting. The discharge rate generally is low in high insolation levels. It is found that the performance prediction of the studied system is difficult due to the nonlinearity relation between the flow and radiation.

Several researchers published many papers in this field. For example, Kumar et al. designs the photovoltaic water pumping system [1]. Ghoneim presents the optimization performance of a photovoltaic powered water pumping system [2]. Dunlop experimentally investigates the effects of different tracking methods on the performance of photovoltaic systems [3]. Also the system performance of standalone PV pumping systems has investigated with different weather conditions by Elgendy [4]. Taylor et al. analyzes the effect of PV array configuration on the PVPS performance [5]. The performance of a small PV power plant under different meteorological conditions has studied by Tobar [6]. Campana et al. illustrates the dynamic modelling of a PV pumping system [7]. Also Albadi et al. studies the modeling and sizing of PVWP system [8]. Koner analyzes the PVPS performance by varying the motor characteristics [9]. The magnetic characteristics of the shunt motor are measured experimentally and fit in polynomial form by Anis [10].

Fooladivanda et al. formulates a joint optimal pump scheduling and water flow problem using the hydraulic characteristics of variable speed pumps [11]. Beckman et al. develops a method to predict the long term performance of PV systems [12]. Jafar presents a method for modeling the output of a small scale photovoltaic solar system [13]. The procedure is implemented in experimental tests and results in predictions of flow rate within 8% of the measured values. The control of pumping system for a single phase induction motor is proposed by Vongmanee using field oriented control [14]. The electrical and hydraulical systems with different photovoltaic sizes are simulated [15]. The vector control of induction motor supplied by PV array is presented by Arrouf [16].

Simulation and experimental investigation of a PVPS are built in Egypt Delta region. A detailed developed model for the calculated radiation is introduced. The experimental values of the water discharge are compared with the simulation results. The actual measurements are collected instantaneously and all meteorological data stored. This paper is classified into six sections. The solar energy model and the system mathematical model are presented in sections II and III. Sections IV, V view the PV pumping system construction and the experimental system setup respectively. Experimental and simulation comparative study are found in section V. The paper ends with the final conclusion.

II.SOLAR ENERGY MODEL

The following equations calculate the diffuse I_d and the global I_g radiations during one year in Delta region of Egypt (paper case study) [17-20]:

$$S_{max} = \left(\frac{2}{15}\right)\omega_S \tag{1}$$

$$S = total\ time - \sum(time\ G_{SC}) \tag{2}$$

$$\frac{H_g}{H_o} = a + b\frac{S}{S_{max}} \tag{3}$$

$$a = -0.110 + 0.235\cos\phi + 0.323\left[\frac{S}{S_{max}}\right] \tag{4}$$

$$b = 1.449 - 0.553\cos\phi - 0.694\left[\frac{S}{S_{max}}\right] \tag{5}$$

$$\delta = 23.45\sin\left[\frac{360(284+n)}{365}\right] \tag{6}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{7}$$

$$H_o = \frac{24}{\pi}I_{sc}\left[1+0.033\cos\left(\frac{360n}{365}\right)\right]\times\left[\sin\omega_S\cos\delta\cos\phi+\omega_S\sin\phi\sin\delta\right] \tag{8}$$

$$I_d = d_1\ t^4 + d_2\ t^3 + d_3\ t^3 + d_4\ t + d_5 \tag{9}$$

$$I_g = g_1\ t^4 + g_2\ t^3 + g_3\ t^3 + g_4\ t + g_5 \tag{10}$$

III.SYSTEM MATHEMATICAL MODEL

A schematic diagram of the PV pumping system configuration chosen for the present study is presented in Figure 1 [21]. The main system components are: photovoltaic array, motor, pump, storage tank and maximum power point tracker (MPPT). The PV array is assumed a fixed configuration to receive the most incident solar radiation. The MPPT is adopted to force the PV array to work at maximum power, thus improving the system efficiency.

Generally, the PVPS consists mainly of photovoltaic array coupled with pumping system. Each one will be discussed as follow.

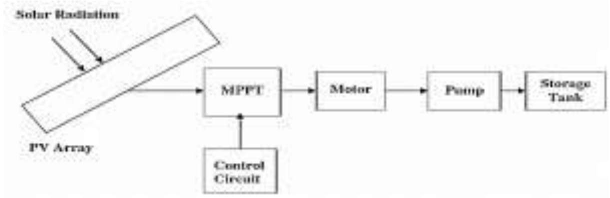


Fig.1. Direct coupled PV pumping system with MPP tracker

A. *PV modeling*

There are many types of PV in the international market; the best of which is the polycrystalline silicon (c-Si) type. The cell efficiency of this type reaches 17.2% as shown in Appendix (Table I). Therefore, it is chosen for this research work. The current-voltage characteristic equation of the photovoltaic cell is given by Roger and Jerry [22] as,

$$I = I_L - I_o\left[e^{\frac{qV}{kT}} - 1\right] \tag{11}$$

Where, the cell fill factor which is a measure of its quality (0.5 to 0.82). The power output of the photovoltaic cell is given by [23],

$$P = FIV \tag{12}$$

B. *Pump and electrical motor performances*

The hydraulic load of a PV pumping system varies with the time and pump flow rate. So, in order to analyze the performance of a PV pumping system, one has to consider the behavior of the well during the system operation. A correct simulation of a photovoltaic pumping system should consider the dependence of the well water level on the water flow rate. The sizing of a PV pumping system depends on the expected hydraulic load. The head versus flow rate profile usually characterizes the pump type. The typical head consists of a static component and a dynamic component as shown in Figure 2 [24].

Tables II and III show the induction motor equivalent circuit parameters and pump manufacture data in appendix, respectively. The electromagnetic torque of induction motor is modeled by the equation 13 [25]. The centrifugal pump power required for lifting the water and the discharge flow rate are given by equations 14 and 15 respectively [26, 27]:

$$T_e = T_L + J\frac{d\omega_m}{dt} + B_m\omega_m \tag{13}$$

$$P_u = D \times \omega_m^3 \tag{14}$$

$$Q = \frac{3600 \times P_u}{(\rho \times g \times H)} \tag{15}$$

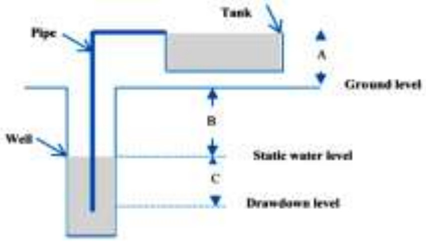


Fig.2. Static and total dynamic head

IV. THE PV PUMPING SYSTEM CONSTRUCTION

A. *System layout model*

Normally, the pumping system consists of three components: the PV array, the motor and the pump. Each component has its own operating characteristics, which are: the I–V characteristics for the PV array and motor and the torque–speed characteristics for the motor and pump. The motor drives the pump whose torque requirements vary with the speed at which it is driven [28]. The motor is operated by the power generated from the PV array whose I–V characteristics depend nonlinearly on the solar radiation variations and on the current drawn by the motor.

The solar cell modules can only provide maximum power at specific voltage level. So there is a unique point on its I–V curve at which the power is at its maximum value for the PV array and the equilibrium operating point of the PV array should coincide with this point for optimum utilization. However, since the maximum power point varies with radiation and temperature, it is difficult to maintain optimum matching at all radiation levels. In order to improve the PVPS performance, a MPPT is used to match continuously the output characteristics of a PV array to the input characteristics of the motor. The MPPT basically consists of a power electronic circuit controlled by a signal circuit, which drives the power electronic circuit to force the PV array to operate at its maximum power point. The MPPT will improve the PVPS efficiency under such conditions.

The modeled system layout is developed in order to dynamically simulate the energy performance of an experimental set-up consisting of solar poly-crystalline silicon PV, DC/AC inverter and induction motor-pump system for the production of domestic water. The set-up also includes a water stratified vertical storage tank. The simulation system layout based on the experimental set-up is depicted in Figure 3 and summarized the main components of the used PV pumping system. The operating principle of the system under investigation and the control strategy can be studied.

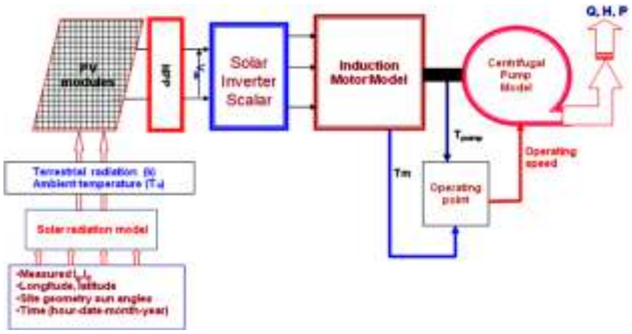


Fig.3. Main components of PV system model under investigation

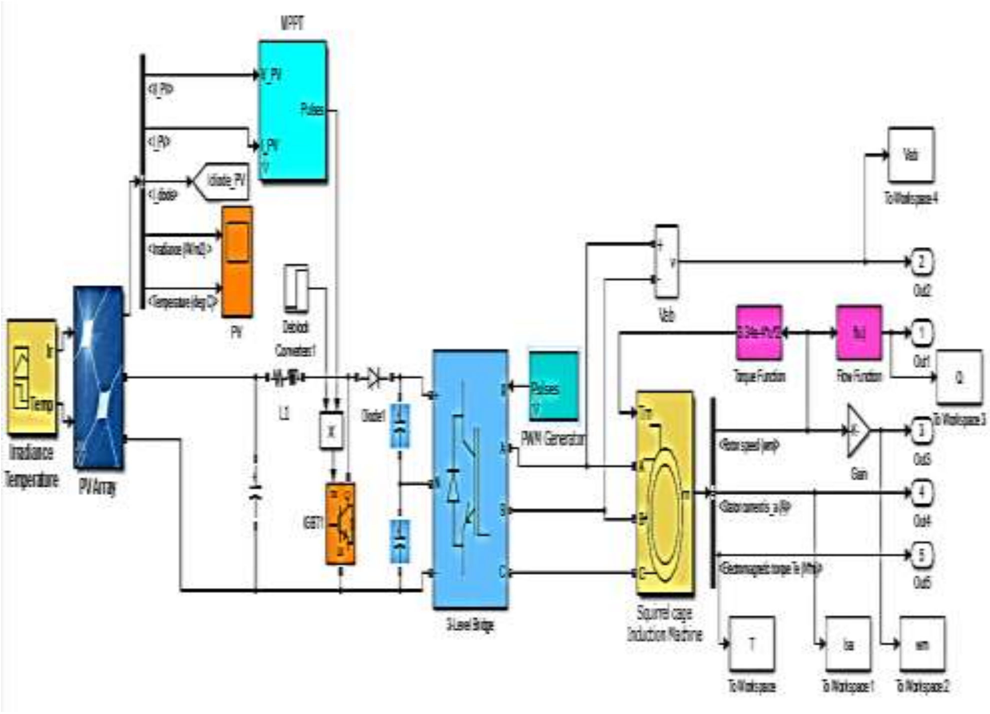


Fig.4. The simulation model of photovoltaic pumping system

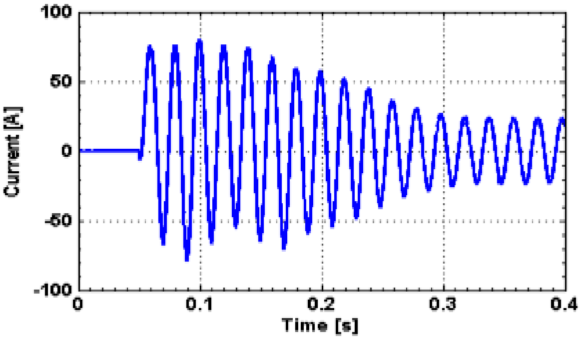
B. Simulation model

In order to compare the obtained data results with experimental measurements, the developed simulation model is dynamically simulated by means of the MATLAB software. It includes a library of built-in components often based on experimental data.

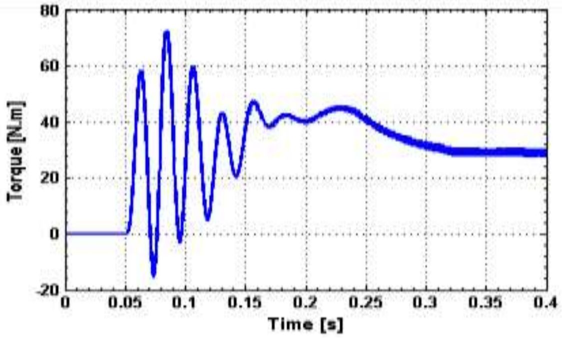
The proposed model is simulated by Matlab/Simulink environment and demonstrated in Figure 4. The effect of radiation variation and temperature can be studied by the proposed Matlab model [29]. The built model takes into account the effect of irradiance, temperature and number of photovoltaic panels. PVPS parameters which are listed in Table V are used as an input for the simulation [30]. The simulation model blocks are used with the input data which given in appendix and the obtained result will discuss in the following part.

C. System performance discussion

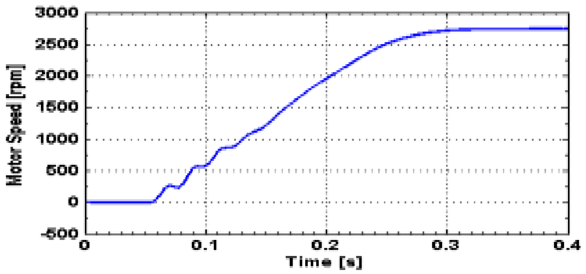
Figure 5 shows the variation of the flow rate which is proportional with the radiation in general way. The flow and the motor speed are increased with the radiation increasing [25]. Table IV shows the flow rate with the solar radiation change. After the speed reaches its rated value, the flow becomes nearly constant. The characteristics of system performance as shown in Figure 6. Figure 7 shows the effect of cell temperature variation on the flow rate.



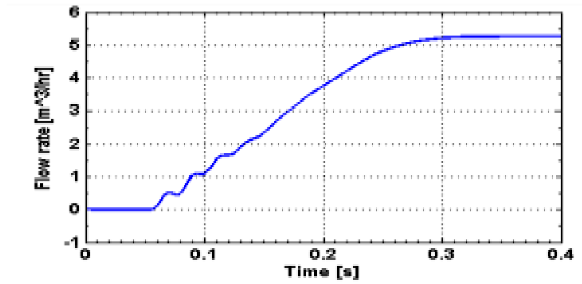
a. Stator current



b. Electromagnetic torque

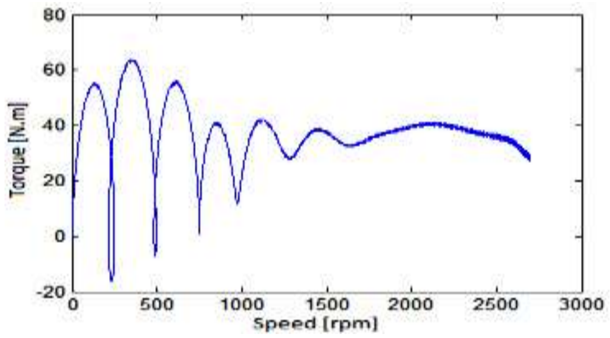


c. Motor speed

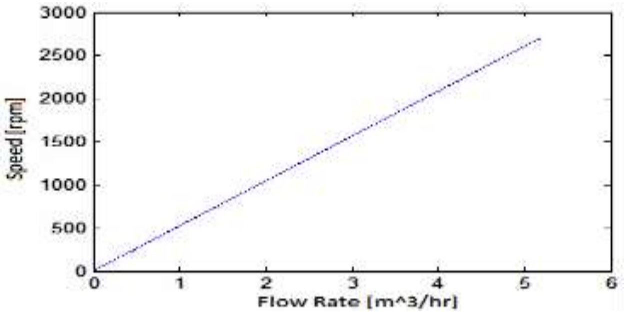


d. Water flow rate

Fig.5. System transient analysis results



a. Speed vs. Torque



b. Flow rate vs. Speed

Fig.6. System performance characteristics

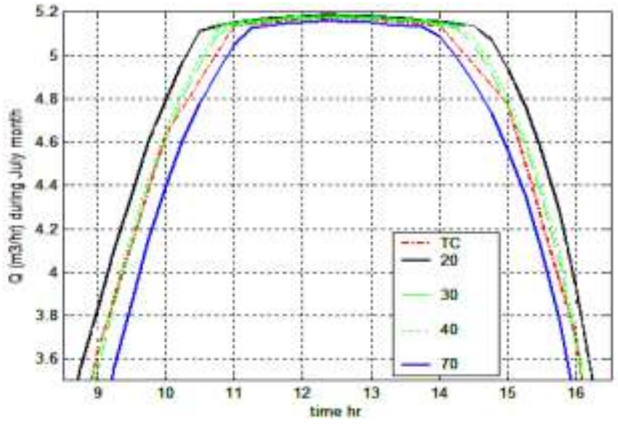


Fig.7. Effect of cell temperature on system flow rate

D. MPPT technique

In this part the Maximum power point tracking illustrated by using the incremental conductance method and compared with the previous obtained results. It is noticed in Figure 8, the output flow in case of without MPPT is larger than with it. So the electrical motor is operated at larger speed which means larger flow rate [31]. It is seen that the efficiency in MPPT system is increased about 1.2 %, however the flow rate is smaller as shown in Figure 9.

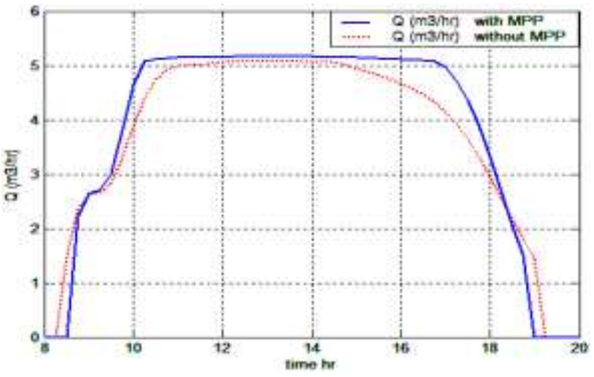


Fig.8. Output flow rate with and without MPPT

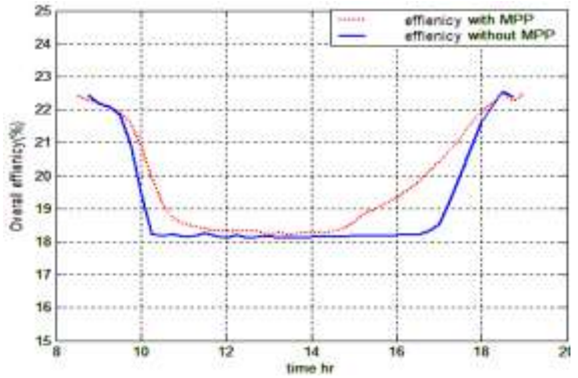


Fig.9. System efficiency with and without MPPT

V. EXPERIMENTAL SYSTEM SETUP

Figure 10 shows the main parts of the experimental system which is composite of two main subsystems, the electrical and the hydraulical systems. The electrical system contains PV array, inverter and motor-pump unit. The second part of the system is the water flow ring. This system included a centrifugal pump with maximum discharge rate $11m^3$/hr and maximum head is 43m, piping system and water storage tanks. The existing PV pumping system is shown in Figure 11.

The weather measurement parameters are the main weather components, which directly related to the performance of PV array such as the solar radiation components and ambient temperature. All these parameters are recorded continuously by measuring devices as shown in Figure 12 and used in the simulation models.

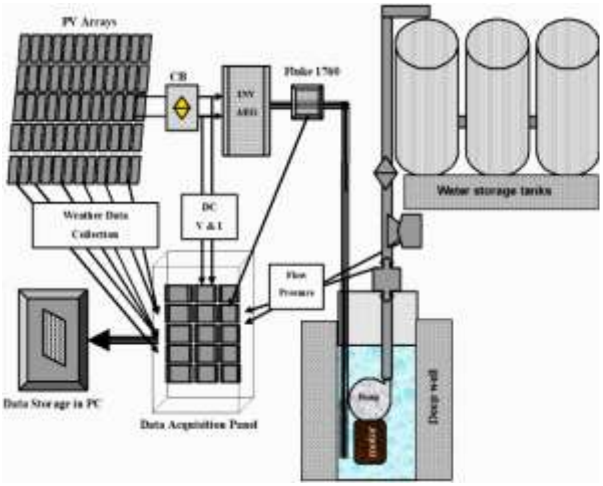


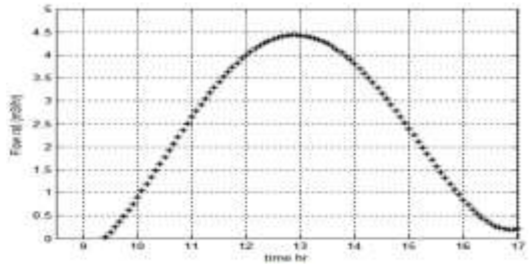
Fig.10. Experimental system setup

Fig.11. The existing PV pumping system at the site

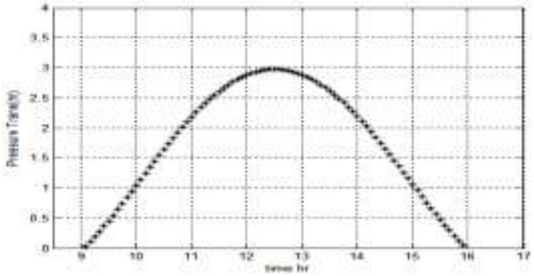
Fig.12. Measuring devices (Radiation, Pressure & Flowmeter [MAG-900])

A. Daily measurements

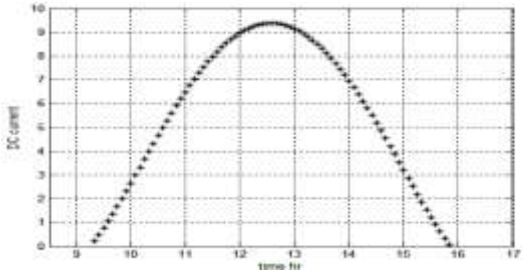
From the obtained measurements, it is found that in Figure 13. The flow rate is increased due to the increasing of radiation till reach its maximum value at the noon. After that the flow rate is decreased till reach zero. The water pressure has the same profile of the flow rate. The cell temperature is measured using two temperature sensors. One is mounted on the upper cell surface and the other is mounted on the bottom cell surface. It is noticed also that the cell temperature is increased with the increasing of radiation. The value of the DC current varies with the radiation. Where the radiation is started with small value, then it increases till reach maximum value at the noon, then it decreases till reach zero at sunset time.



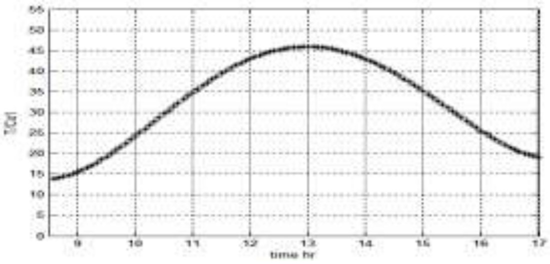
a. Flow rate



b. Water pressure

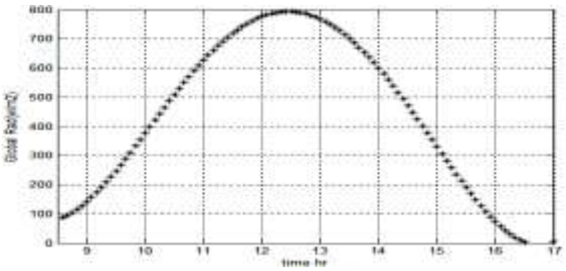


c. DC current of PV module



d. Cell temperature

Fig.13. (a,b,c,d &e) One day measurements



e. Global radiation

Fig.13. (a,b,c,d &e) One day measurements

B. Monthly discharge analysis

The monthly water discharge is calculated from the daily discharge value and compared with the measured values. It is found that the error between measured and estimation has acceptable values are less than 5% for all year months. The yearly discharge value can be estimated from the monthly values and then compared with the measured value the percentage error obtained is less than 1.032%.

VI. COMPARATIVE STUDY BETWEEN SIMULATED AND EXPERIMENTAL MEASUREMENTS

The simulation results are compared with the measured hourly values of month, which are calculated from the daily measured values. However, there are some deviations at the sunrise and sunset time due to the error in solar radiation values. The calculated solar radiation values are close to the measured values. The comparison shows a good agreement obtained between the simulation and the measured values.

VII. CONCLUSION

The presented paper focuses on the performance of an experimental setup of PVPS. The experimental setup is purposely constructed in order to evaluate the system performance and currently installed at delta location (Egypt). The mathematical model of the PV pumping system using the original equations for the different components is proposed.

In this research, the long term performance of the PV direct coupled with pumping system is introduced. The PVPS operation during the transient and steady-state operation is deduced. The simulation studies in cases of solar radiation values are presented. The monthly estimated performance from the daily hourly average is calculated. The obtained results give a good agreement between the simulation and experimental measurements. The error between the calculated monthly flow rate and the measured is less than 5%.

The effect of temperature is studied in the paper which it is found that with high temperature the quantity of the output water is reduced. This indicates the important of cell cooling system. The study is included using MPPT technique which improves the system performance. The proposed system efficiency is increased by 1.2% over the conventional one.

Also results are given in graphical form and simple equations have shown the daily pumped water per unit array area with specific system parameters. Moreover, results for different system parameters can also be easily obtained. However, it is recommended to facilitate the system with a suitable PVPS.

VIII. APPENDIX

TABLE I

PV array constants

Parameters	Value
Type of modules	Polycrystalline silicon (c-Si)
Maximum power current	2.2 A
Maximum power voltage	20 V
Optimized cell efficiency	17.2 %
Short-circuit current	2.41
Open-circuit voltage	22.4
Nominal peak power	150 W + 2 %
Operating temperature	−40 °C to +90 °C
Maximum system voltage	800 V DC
Power temperature coefficient	−(0.5 ± 0.05) %/K

TABLE II

Induction motor equivalent circuit parameters

Parameters	Value	Parameters	Value
Number of Poles	Two	Inertia (J)	0.02 kg.m^2
Nominal Power (P)	3 hp	Friction Factor (B_m)	0.005752Nms
Line Voltage (V)	380V	Mutual Inductance (L_m)	0.2037 H
Stator Resistance (R_s)	1.115Ω	Stator Inductance (L_s)	0.005974 H
Rotor Resistance (R_r)	1.083Ω	Rotor Inductance (L_r)	0.005974 H

TABLE III

Pump manufacture data

Parameter	Value
Total Head, H	4.3 m
Flow Rate, Q	11 m^3/hr
Water Density, ρ	1000 kg/m^3
Earth Gravity, g	9.81 m/s^2
Water Discharge, V	5.25 m^3/day
Efficiency, η	50 %
Average peak sun hour, G	4.8 kWh/m^2/day
Load Speed Dependent Constant, D	6.57x10^{-4} N.m.s^2
Distribution pipe diameter (PVC)	1 "

TABLE IV

At TDH of the well = 2 meter and Cell Temperature = 46 °C;

G [W/m^2]	200	300	400	500	600	700	800	1000
ω_m [rpm]	2330	2515	2620	2650	2665	2675	2710	2790
Q [m^3/hr]	4.5	4.7	4.9	5.0	5.05	5.1	5.2	5.3

TABLE V

Data of different components of the PV pumping system

Parameter	Value
PV Manufacture	AEG-Germany
Pump Type	BP16–Grandfous
PV panel	6 W, 500 mA, 12 V
Battery	Lead Aced, 70 Ah and 12 Volts
Inverter	1500 W, 10–15 V DC / 220 V AC, 50 Hz
Transformer	220 V / 12 V AC

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